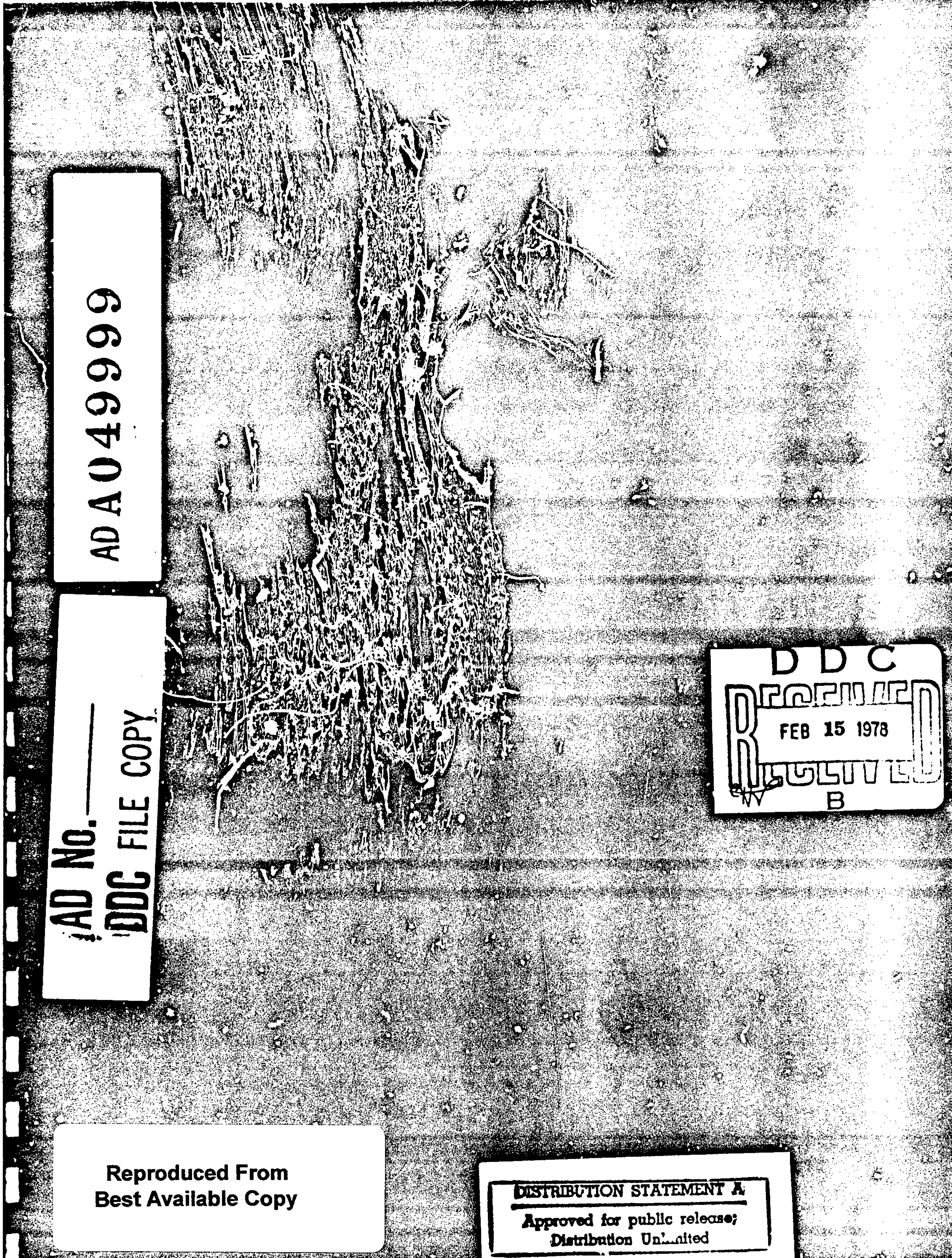

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MORPHOLOGY OF DESIGN OF AEROSPACE SYSTEMS WITH INCLUSION OF HUMAN FACTORS

FINAL REPORT

Benjamin Ostrofsky

Principal Investigator

University of Houston

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ABSTRACT

This research report is intended to provide a basic clarification of the decision structure and methodology for the design of a high technology, large scale system with emphasis on integration of human factors and their associated metrics. The report summarizes and relates the design morphology to current USAF methodology for the management of system design, defines and classifies human factors which influence the decision structure of design, and clarifies the nature of subjective and objective requirements which are inputs to the decision structure. The conceptual framework developed as an effective approach to the solution of the problem of human factors inclusion into the design morphology is that of a three dimensional matrix representing the relationship among human factors, the design steps, and the current literature. This relationship allows for explicit human factors inclusion during the preliminary design phase of a new system and the resultant inclusion in the criteria function for the optimal design configuration.

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1.0 INTRODUCTION

The research resulting from this project is intended to clarify the decision structure and methodology for the design of a high technology, large scale system with emphasis on integration of human factors and their associated metrics. This effort was initiated after many years of study and development of a methodology [14] that successfully integrates the necessary decisions to efficiently utilize resources in order to meet a design need. In effect, a morphology of design emerged from which economic applications can be readily achieved. The potential to the United States Air Force (USAF) of this morphology was recognized by the members of the Air Force Office of Scientific Research (AFOSR) and the Air Force Human Resources Laboratory (AFHRL), and the problem of effectively including human factors into the design or plan for USAF systems was chosen as the initial vehicle for study.

More specifically, this study reviews recent developments in the design morphology, identifies relevant human factors, and clarifies subjective and objective inputs into the decision structure. A bibliography was developed [15] to accomplish two specific study goals. The first was to permit the University of Houston researchers to supplement their awareness of the current developments in both the design literature and human

factors literature. The second goal was to provide a current, relevant compendium of annotated titles that are useful to the researchers and to other agencies and individuals. These goals were met.

Of major concern to USAF is the proper integration of human factors into emerging systems so that performance criteria for these systems will properly reflect the influence of these factors. There appears to be a reluctance on the part of equipment designers to accept this "soft" data as an input to the design of equipment, particularly when there is difficulty in meeting the more easily identified hardware performance requirements. Hence, the improper inclusion of human factors in USAF equipment affects results in the type of equipment which can perform well when operational, but achieving the adequate operational state cannot be met with the planned human resources.

Designers have shown a willingness to include human factors data that have been quantified and are available to the design process [5, page 8] What is needed is a methodology that explicitly allows for the inclusion of these relevant factors into the design process.

Prior research [1], [14], [17], has resulted in such a methodological approach to the design process and its

application to the Air Force design problem will be through the accomplishment of three major objectives:

1) Clarification of the decision structure and methodology for the design and implementation of a high technology, large scale system

2) Definition and classification of human factors which influence the decision structure of design

3) Investigation of the analytical methods for the successful integration of qualitative and quantative information into a multivariate criterion function. The first two have been accomplished within the scope of this research; the last is planned for the next two years.

1.1 SCOPE OF THE PROJECT

The research begins with a review of the literature describing design decision structures and/or dealing with human factors relevant to system design. The human factors are then classified for integration into the design and for feasibility of quantification.

The design morphology used is that of Ostrofsky [14]. This particular rationale emphasizes the system life cycle and the clarification of subjective and objective inputs to the design decisions. In addition, a detailed description of the process demonstrates the inclusion of

human factors in system design. Examples showing the importance of human factors analysis in design considerations are given.

This research will construct a three dimensional matrix representing the formal relationship among human factors, the steps of the design morphology, and the existing literature. This is accomplished by formally defining the major (or basic) categories of human factors as they relate to each step in the design morphology. The major publications in the current human factors literature as identified by the researchers [15] are then related to the respective human factors-design pair. To facilitate the relating of the current literature to the human factors categories a limited demonstration data base is developed (see Appendix B).

Finally, potential areas for future investigation including needed analytical design methods are defined

1.2 BACKGROUND

The system engineering/system management procedures developed by USAF [17] during the 1960's identified the philosophy and the details of implementation for USAF systems. This documentation went to the extent of identifying reporting details for each activity during the

system life cycle and, while it left the designer free to improvise, it constrained his activities to definable and reportable categories.

In the 1970's guides for acquisition management were made available [19], [20], [21], [22]. One pamphlet [19], for example, covered the general considerations during the management of a program and is of interest to all program management personnel. It provided an overview of project activities from conception through deployment and reflected the recent changes in acquisition policy issued by the Department of Defense (DOD). This guide will be used in this research to establish a basis for the Air Force system life cycle and design process.

Independently of the USAF, Professor Asimow [1] in 1962 delineated a philosophy and a rationale for the design of a technological system. This rationale defined a decision structure required to use resources optimally in attempting to meet design objectives.

In 1962 Ostrofsky began formal study of this methodology and developed Asimow's rationale into a viable set of procedures for accomplishing the decisions inherent in the design of a system. These procedures were delineated in detail and redefined by constant application in engineering and management classes in the university and practice

in industry until a set of rules and theorems concerning designer behavior and decision sequencing were clearly established and publishable [14].

The inclusion of human factors in system design has been the topic of extensive research in recent years. A brief review of this research is given later in this report, as well as reviewed in the bibliography. However, there appears to be a gap between human factors analysis and system design. This research attempts to bridge the gap by showing how human factors properly identified, classified, and quantified, can be included into the design process.

1.3 LITERATURE REVIEW AND BIBLIOGRAPHY

A review of the literature describing the design decision structure as it relates to the development of aerospace systems as well as identifying the human resource factors relevant to the design structure has been conducted. The result of this activity is an annotated bibliography [15] which is used in this research to complement the design morphology by identifying and categorizing the human factors for inclusion in the decision structure.

Three basic points have emerged from this literature search. First, both the engineering design and the human

factors literature voice strong agreement on the need for the integration of human factors into the system design process. Although a practical and consistent approach has not yet emerged, both areas are sufficiently developed to consider the influences upon each other in a unified procedure for system design.

Secondly, the human factors data currently available generally lack standardization and clarity for design applications. While special purpose data files have been created, the very aspect of their specialization often limits their applicability to the many broad disciplines required for large scale system design [7].

Finally, there appears to exist an urgent need for an interdisciplinary data base describing and quantifying the human factors essential to system design. The ensuing research will attempt to make some progress in this direction.

It is apparent that no one, relatively brief, literature search such as this can completely cover the existing literature in both the design decision structure and the human resource factors. However, this effort is offered as a beginning and should be continually supplemented and updated.

2.0 U.S. AIR FORCE LIFE CYCLE DESIGN

2.1 BACKGROUND

Early, the United States Air Force recognized the need for viewing long term effects of their decision making as it related to the design of new systems and to the ability to support such new systems in the field. The design and planning of a new system, with regard to the costs and benefits throughout the life of the system, lead to System Life Cycle Planning, and many documents have been published by USAF to guide designers in their path to successful achievement of goals. However, System Life Cycle Planning has never been a static concept. Rather, it has been a basic philosophical approach which has lent itself to refinement and modification over the years as methodology has advanced with the state of the art, as the exigency for military hardware demanded, and as the forces of political pressure were satisfied.

A review of the Air Force literature [17], [18], [19], [20], [21], [22], describing the system acquisition process over the past 10-15 years does reveal, however, a thread of continuity as to how the Air Force views the life cycle design process. Six phases of the life cycle design process have been identified in this study (see Figure 2-1). These phases and the associated definitions

are a composite view or a perspective of the life cycle phases utilized by the Air Force. Because the Air Force acquisition process is dynamic and specific terms and definitions are subject to change, this view of the Air Force's life cycle phases provides a common basis for analysis and methodological development.

CONCEPTUAL
VALIDATION
FULL-SCALE DEVELOPMENT
PRODUCTION
OPERATIONS
RETIREMENT

Figure 2.1 Six Phases of U.S. Air Force Life Cycle Design Process (Adapted from [17])

2.2 LIFE CYCLE PHASES - A PERSPECTIVE

2.2.1 Conceptual Phase

The conceptual phase begins when national defense objectives, intelligence estimates, threat information, foreign technology, conceptual studies, and feasibility

studies provide Air Force planning organizations with the information necessary to determine the requirement for a new capability [17, page 28]. The conceptual phase extends from the determination of a needed operational capability to the program decision which authorizes the initiation of the validation phase [19, page 2-1]. For the purposes of this discussion it is assumed that a given system proceeds through the life cycle phases, remembering that not all capabilities which are identified as being needed will survive the evaluation and analysis of the design process, let alone the political process necessary to obligate the funding needed to bring a given system on line.

"The conceptual phase is a highly iterative process with activities performed simultaneously and/or sequentially as the basis for the acquisition are established by policy, fiscal, analytical, experimental, and engineering efforts accomplished at the various levels within the Department of Defense. The objective of ...(this phase)... is to define and select the system concepts which warrant further development." [19, page 2-1].

The output of the conceptual phase is an identified preferred system configuration along with any identified alternative system configurations. Four points must be

satisfied before the design process may proceed to the next phase:

"1) Mission/performance envelopes are adequately defined, technically feasible, and capable of achieving the stated objectives within reasonable cost and schedule constraints

2) Military, technical, and economic objectives are sound, needed, reasonable, and well defined

3) Major uncertainties are identified for further investigation during the validation phase

4) Preliminary cost and schedule estimates are based upon sound analyses and are commensurate with the degree of certainty in the other aspects of the program." [19, page 2-1]

2.2.2 Validation Phase

The purpose of the validation phase is the testing and refinement of the system concepts by extensive study and analysis, hardware development, or prototype testing. This may be the first phase in which a formal request for proposal (RFP) solicitation will be used to initiate the contracting process [22, page 40]. During the validation phase, the system characteristics (design requirements) are translated into performance-type specifications

(as opposed to restrictive detailed design specifications). To accomplish this objective the system functions are subdivided into system segments, subsystems, and components with the corresponding performance requirements and design constraints being identified [19, page 3-5]. The development of prototypes or models usually occurs for the evaluation of design, performance, and production potential [19, page 3-7]. A major activity during this phase is the performance of engineering design studies which are part of an optimization process aimed at achieving a balance between such factors as total cost, schedule, and operational effectiveness [19, page 3-8].

Before proceeding to the full-scale development phase, the following objectives of the validation phase must have been satisfied:

"1) System trade-offs (studies) have produced a balanced and realistic set of performance parameters.

2) Risk areas have been identified and reduced to acceptable levels.

3) Cost/schedule estimates for full-scale development are acceptable.

4) Contractual aspects are sound (type appropriate to risk and funding related to milestones)." [19, page 3-13]

2.2.3 Full-Scale Development Phase

During the full-scale development phase, the complete system, including support items, is brought through the final design phase, a fully operational version of the system fabricated, and testing and evaluation is conducted by contractors and the Air Force. An initial version of the system which closely approximates the final product is produced, the engineering documentation necessary to enter the production phase is developed, and the system evaluation test results which demonstrate the attainment of the required performance parameters are conducted [19, page 4-1]. In sum, the output of this phase is a system that has demonstrated its supportability, producibility, and operational feasibility [21, page 4].

During this phase, the design activity develops detailed drawings for the fabrication of the preproduction prototype, emphasizing the interfacing of system components and the system with other systems. The engineering effort is primarily concerned with system design integration, interface control, the optimization of the final design, effectiveness analysis, and the resolution of known or potential problem areas [19, page 4-2]. And from the production standpoint, the analysis of producibility and the identification of new production problems is intensified.

Given that the above activity is successfully

concluded, the major milestone remaining for this phase is the approval to proceed into the production phase. The approval decision (by the Secretary of Defense for major systems) follows a review of the system's develment which must confirm:

"a) the need for producing the defense system in consideration of threat, estimated acquisition and ownership costs and potential benefits in contest with overall ... (Department of Defense)... strategy and fiscal guidance

b) that a practical engineering design, with adequate consideration of production and logistics problems is complete

c) that all previously identified technical uncertainties have been resolved and that operational suitability has been determined by test and evaluation

d) the realism of the plan for the remainder of the program " [20, Attach. 2, pages 9,10]

2.2.4 Production Phase

The purpose of the production phase is to efficiently produce and deliver to the operating unit an

effective supportable system at optimum cost [19, page 5-1]. To satisfy these system requirements the producer must maintain efficient control of the factors of production (manpower, material, and real property facilities), quality, and finished product inventory [19, page 5-3].

To accomplish this objective the Air Force maintains a tight surveillance of contractor production operations to monitor progress assessment; detection, reporting, and timely solution of production difficulty; evaluation of documentation; review of manufacturing methods and techniques; and assessment of contractor production management [19, page 5-2].

The testing begun during the full-scale development phase is often continued during the production phase. In addition, the using command initiates operational testing and evaluation of early production models to detect and correct unacceptable deficiencies at the earliest opportunity. This testing includes an assessment of the system's operational capabilities and develops the most effective operational tactics, techniques, doctrine, and standards.

Because of the long production run times involved with most of these high technology systems, the system end-items become available for distribution to the user

over an extended time horizon. This concept of a protracted delivery scheme is referred to as the deployment of the system. System deployment overlaps the production and operation phases of the system life cycle, and officially ends with the receipt of the final production unit.

2.2.5 Operations Phase

The operations phase begins with the receipt of the initial system end-item by the using organization. This phase is concerned with the employment of the system to counter the threat and/or provide the capabilities for which it was designed. Included is an on-going process of developing doctrine, tactics, and standards for employing the system; the training of operators and support personnel; integrated logistics support; and the evolution of proposed system modifications to meet a changing operational environment and/or maintain or improve system specifications. The operations phase may extend for decades, with its termination dependent upon the system's ability to satisfactorily provide a needed capability. When the system is no longer needed, its orderly retirement becomes necessary.

2.2.6 Retirement Phase

The retirement phase begins when the system is

removed from active operational service. The federal government operates under an elaborate system for the redistribution, sale, and the recycling of obsolete systems. However, the main concern form the perspective of this report, is the active planning and consideration of system retirement in terms of planning a system's total life cycle. The criticality of this view might be evidenced in the need to explicitly plan for the safe disposal of nuclear wastes or other undesirable effluents or by-products of a complex system. The authors did not find mention of this aspect of systems design explicitly discussed in the Air Force publications reviewed. The legal requirements for performing environmental impact studies, however, do provide for the implicit inclusion of this factor.

3.0 DESIGN MORPHOLOGY

3.1 BACKGROUND - INTRODUCTION

The introduction of this study stated the purpose of this research to be the application of a methodology consisting of a sequential decision structure necessary for the design of a USAF system. To achieve this purpose, Ostrofsky's design morphology [14] is used with USAF systems taken as a direct application.

Ostrofsky notes that the methodology does not of itself guarantee a successful solution to the design problem: no methodology can do this for all problems. However, it does increase the likelihood of reaching the "best" possible solution with an efficient use of available resources. As will be seen later, "best" is defined in terms of criteria which are explicitly delineated. Since some criteria are directly related to human factors, the inclusion of these human factors into the emerging system by this methodology is critical and is approached directly.

This morphology also establishes a close relationship between the design process and the life cycle of the system under consideration. Design and production-consumption phases are identified and can be directly

related to the USAF life cycle phases discussed in the preceding section.

The design morphology with its wide applications is described in the text [14] and represents a comprehensive philosophy for system design. The book then represents the prime reference for this discussion. Moreover, since the morphology semantics are very precise, some basic definitions are required and are given, as needed, throughout this discussion.

A direct comparison between the USAF life cycle and that of the design morphology is given in Figure 3.1. Note that there exists a one-to-one correspondence between the phases. Also, note the absence of the distribution phase in the left-hand column. This distribution phase, which accomplishes the phase-in of the system for its users, closely corresponds to deployment which overlaps both the production and operations phases of the USAF system life cycle. The definitions for production, operations, and retirement of both approaches are almost equivalent and will be discussed in the next section. The three design phases that yield the final form of the system include the sequential activities which structure the form and content of the design process.

	AIR FORCE LIFE CYCLE PHASES	DESIGN MORPHOLOGY PHASES
DESIGN PHASES	CONCEPTUAL	FEASIBILITY STUDY
	VALIDATION	PRELIMINARY ACTIVITIES
	FULL-SCALE DEVELOPMENT	DETAILED ACTIVITIES
PRODUCTION-CONSUMPTION PHASES	PRODUCTION	PRODUCTION
		DISTRIBUTION
	OPERATIONS	OPERATIONS
	RETIREMENT	RETIREMENT

Figure 3.1 A Comparison of U.S. Air Force Life Cycle Phases to the Phases of the Design Morphology

The "feasibility study " is the first design phase and corresponds to the conceptual phase. Its purpose is the development of a set of useful solutions to the design problem. Thus it identifies the needs, formulates the problem, synthesizes a set of solutions, and screens them. The identification of the problem is accomplished by means of an input-output matrix, where the rows are

the production-consumption cycle phases (production, distribution, operations, and retirement), and where the columns consist of intended (or needed) inputs, environmental (or existing) inputs, and desired and undesired outputs (see Figure 3.2). As will be discussed later, this matrix plays an important role in facilitating the inclusion of human factors in the design process. Each synthesized solution is referred to as a candidate system which, by definition, is "a particular configuration of each of a group of subsystems such that every function and activity related to the total system would be accomplished if the candidate system were completely developed" [14, page 47]. Candidate systems are synthesized from concepts or approaches to the solution of the problem. Since the objective of the feasibility study is to select the solutions which warrant further development, the candidate systems must be screened to meet the fiscal, analytical, experimental and engineering requirements and policy of the Department of Defense.

	Inputs		Outputs	
	Intended	Environmental	Desired	Undesired
Production				
Distribution				
Consumption-Operation				
Retirement				

Figure 3.2 The Input-Output Matrix

The second design phase is "Preliminary Activities," and corresponds to the validation phase. This phase identifies the "best" candidate system in terms of well defined criteria. For this purpose, criteria are related to parameters and to attributes of the alternatives, and a value is assigned to a criterion function for each candidate system. Once identified, the chosen system is tested and its performance over the life cycle is predicted. Engineering design trade-off studies discussed earlier can be considered as the major activity of this design phase.

The third, and final design phase is the "Detailed Activities" or full-scale development, and is undertaken once the optimal or "best" candidate system has been chosen. These activities include the adequate review of all information and data to this point, the development of details of the system by means of engineering drawings, assembly instructions, the specification of organization, production and operations plans, and finally, experimental constructions. If these activities are not completed prior to the production phase, costly changes will probably ensue which usually eliminates most of the time savings anticipated.

Note that of necessity, knowledge of the immediate

design problem is usually incomplete when decisions are made, hence causing the iterative nature of design by leading to a reexamination process throughout the morphology. Furthermore, the designer must pursue a policy of least commitment stated as follows: "In progressing from step to step in the morphology, no irreversible decision should be made until it must be made" [14, page 21]. This principle thus allows the designer to avoid eliminating an alternative which may turn out after reexamination to be optimal, and proves to be the most efficient procedure for completion of the design activities.

3.2 PRODUCTION - CONSUMPTION PHASES

The activities of the design phases are accomplished to anticipate the needs of the production-consumption cycle. Obviously, then, the designer's problem is to understand the requirements of each phase of the production-consumption cycle to a depth adequate for resolution of problems during these phases, since changes occurring after the start of the production phase will be much more costly than changes or iteration occuring prior to the start of the production phase. This section, then, describes the nature of the production-consumption cycle phases.

3.2.1 Production

Production is the set of activities for the "transformation of goods or services into a more useful form" [14, page 201]. "As the first class of activities in the production consumption cycle, many of the major needs and constraints for the designer-planner emerge from this phase of the activities" [14, page 9].

3.2.2 Distribution

Distribution, also referred to as deployment, accomplishes the phase-in of the production output to the operator or user. The distribution activities should provide flexible and effective methods for accomplishing the transfer and integration of the produced system to the required locations and for assuring the start-up of smooth operations.

3.2.3 Operations

In the operations phase, the system is operated to meet the user needs directly. The operation of the system is usually more difficult to control than production and distribution because of the greater variation in the characteristics of the users. On the other hand, this phase generally determines the major criteria for system acceptance, thus creating the following designer's dilemma: "...how to reasonably limit

the expenditure of resources in determining operational requirements while simultaneously obtaining the best overall performance from the entire morphology" [14, page 12]. While no universal solution to this problem exists, the morphology gives a structured decision process which provides the designer with a clearer insight into operations requirements and performance, and results in more effective systems for the criteria defined.

3.2.4 Retirement

During this phase, the system is withdrawn from its intended functions in operation. This implies either the replacement of the system or a modification of its original uses. In both cases, there are many important implications for the design of the system.

3.3 DESIGN PHASES

The three design phases - feasibility study, preliminary design, and detail design - consist of a number of sequential activities which ensure a complete and thorough approach to the solution of the problem. These activities provide a logical transition from the clear and complete definition of a need to the detailed development of a system to satisfy that need. It is important to note, however, that while the sequence of the

design steps is relatively rigid, the iterative nature of the process permits the full exercise of judgement and past experience throughout the design process. So that, as the design process continues and additional knowledge is gained, iteration of previous design activity is required to improve the decisions made at these earlier steps.

3.3.1 Feasibility Study

The purpose of the feasibility study is to synthesize a set of solutions to meet the identified needs. Since this phase of the design process identifies the set of candidate systems from which the optimal alternative emerges, any inadequacies in this phase are carried forward to subsequent phases. The feasibility study is thus the foundation for the design phases to follow and can appreciably simplify subsequent decisions when accomplished properly.

A feasibility study consists of four important steps: 1) analysis of the needs, 2) identification and formulation of the problem, 3) synthesis of solutions, and 4) screening of the candidate systems.

First, the needs must be clearly defined in order to justify the subsequent expenditure of resources. If

this step is not adequately accomplished, the probable solution resulting from this morphology will not meet the original needs and substantial losses may be incurred. Research of the past, present, and future requirements of the production-consumption cycle of the system must be conducted resulting in an objective definition of the needs. Objectivity is required to eliminate as much as possible the prejudices and preconceptions of the designer. Often, a test program to verify the existence of certain needs is used in the analysis, and finally, a statement of goals emerges and the designer is ready to proceed to the identification and formulation of the problem, the next step.

This relates in detail the needs previously defined to the production-consumption phases of the life cycle and bounds the various aspects of the problem into a finite set of objectives so that the designer can proceed with realistic goals in view. This is accomplished with the use of an input-output matrix (Figure 3.2) in which desired and undesired outputs as well as intended and environmental inputs are identified as completely as possible at this stage of the design process. While environmental inputs represent existing conditions and available resources, the intended inputs are supplements to the environmental inputs needed to enable the achievement of outputs. The resulting matrix includes in each

cell descriptors which are a function of the knowledge available at the time the matrix is constructed. The continuous improvement in the state of knowledge concerning the problem and consequently, the improvement of the input-output matrix as the designer proceeds through the morphology are examples of the iterative nature of design.

Bounding the problem by means of the input-output matrix provides an efficient approach to the synthesis of solutions to the design problem. This creative step of the design process results in concepts and candidate systems [14, page 47] which are tailored to the uniquely defined needs. The concepts, which are basic approaches to the solution of the problem, relate to the depth defined by the needs analysis and problem identification. For every concept, the different functions to be accomplished are then identified and grouped into subsystems. Next, alternative candidate systems are obtained by combining exactly one alternative for each subsystem within a concept such that every function related to the total system is accomplished. Note that the level of the concept, and thus, the number of candidate systems, are directly related to the pointedness of the needs.

Finally, the development of a set of candidate

systems must be accompanied by a preliminary examination which assures that the systems being considered are feasible. The screening of the candidate system relates to its:

a) physical realizability, defined as "the ability to actually achieve the combination of subsystems or functions defined in the concept" [14, page 57] ,

b) economic worthwhileness, or the value received from the completion of a given candidate will merit the expenditure of resources required to develop it, and

c) financial feasibility, which identifies the actual sources of funds needed to accomplish the project.

While there may be other, more explicit screens for a given system, these "macro" screens serve to relate to all systems.

3.3.2 Preliminary Design

The set of possible candidate systems synthesized in the feasibility study becomes the input to preliminary design. The purpose of preliminary design activities is to select the candidate system which best meets the

identified needs. This is accomplished through an optimization process which permits the designer to fully comprehend the nature of his "design space." The activities are: 1) preparation for analysis, 2) definition of design criteria, 3) definition of parameters, 4) criterion modeling, 5) formulation of a criterion function, 6) analysis of the parameter space, 7) formal optimization, 8) prediction of system behavior, and 9) testing and simplification.

Quite often, there is a time gap between the completion of the feasibility study and the beginning of the preliminary activities. This time period can be used to reassess the decisions of the first design phase (the feasibility study) in light of new information and to reexamine relationships between needs, problem identification, concepts and candidate systems. A good approach to this reexamination is to group candidate systems by attributes or by subsystems and to list advantages and disadvantages of the different groups. The purpose of this activity is twofold: first, to understand the nature of the criteria to be met by the emerging candidate system; second, to study the nature of candidate systems for a given concept and the qualities of the different concepts.

The ideal design seeks the "optimum" candidate system, the one which is theoretically the most favorable for some defined criteria. However, any design methodology must settle for the "optimal" candidate system, the most favorable for the criteria and set of candidates defined. Thus, criteria present the measures against which performance of a system is evaluated. These criteria must emerge from the needs analysis and problem formulation of the feasibility study, and usually, from the output columns of the input-output matrix. A major cause for the inadequacy of many systems is the fact that "any criterion not considered will not be included in the choice of the optimal candidate" [14, page 80]. Thus, when an element is in reality a criterion but not included as one, a design methodology for finding the optimal candidate will not include this criterion no matter how explicit the methodology may be. The adequacy of the needs analysis and problem identification tends to ensure that all the important criteria are included.

When more than one criterion exists, a relative value or weight, a_i, must be assigned to every criterion x_i (Figure 3.3). Furthermore, it has been shown [14, Appendix C] that the a_i should be structured such that

$$\sum_{i=1}^{n} a_i = 1 \qquad 0 \leq a_i \leq 1 \quad (1)$$

"Since the a_i are vital to the choice of the optimal candidate system, any data or information that can be obtained to help evaluate them may be worth the resource expenditure required" [14, page 84].

Criterion, x_i	Weight, a_i
x_1	a_1
x_2	a_2
x_3	a_3
.	.
.	.
x_n	a_n

Figure 3.3 Criteria and Relative Weights

Usually, the criteria defined for a given system cannot be directly measured for every candidate system. The criteria must then be related to measurable variables which can emerge from an understanding of the nature and characteristics of the set of candidate systems (Figure 3.4). Three different types of criterion constituents can be distinguished:

a) Parameters, or elements that are directly measurable, denoted by y_k

b) Submodels, or elements that can be modeled

from other parameters, denoted by z_j

c) elements which cannot be directly measured. If these are crucial to the adequate assessment of candidate system performance, some method must be devised to estimate them quantitatively. This usually implies the addition of laboratory or field studies.

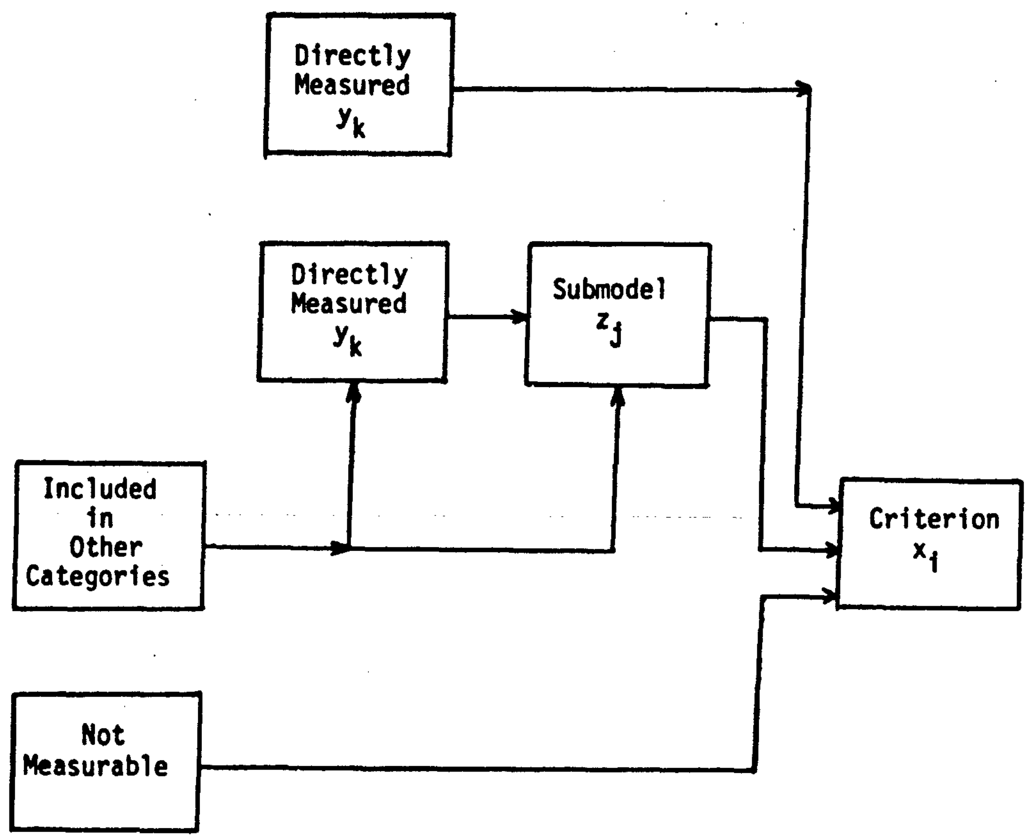

Figure 3.4 Constituents of a Criterion for a Set of Candidate Systems

The procedure which consists of assigning a code to every criterion element, according to its type, is repeated for all the criteria (see example in Figure 3.5). The elements are then reexamined for consistency (no synonyms), completeness (exhaustive listing), and compactness (combination of common elements). Finally, the submodels are related to their corresponding parameters (see example in Figure 3.6).

Criterion	Elements	Code
x_1	e_1	b
	e_2	a
	e_3	a
x_2	e_4	c
	e_5	b
	e_6	a
	e_7	a
	e_8	b

Figure 3.5 Criteria and Elements

		x_1				x_2			
	z_1	z_2	z_3	z_4	z_5	z_6	z_7	z_8	z_9
y_1	X	X	X		X				
y_2	X		X	X			X	X	
y_3	X	X		X		X	X		X
y_4		X		X	X		X		X
y_5		X	X	X		X		X	
y_6	X	X	X		X		X		X

Figure 3.6 Relating Submodels to Parameters for all Criteria

Since the objective is to determine the optimal candidate system, all criteria are combined into a single criteria function and the performance of each candidate system is evaluated by defining the value of this function for that system. The criteria function is constructed from a combination of criteria and their respective relative values (Figure 3.7). A cardinal scale emerges from this criteria function, and permits the identification of the optimal candidate system as well as establishing a ranking for the candidate systems in the defined set.

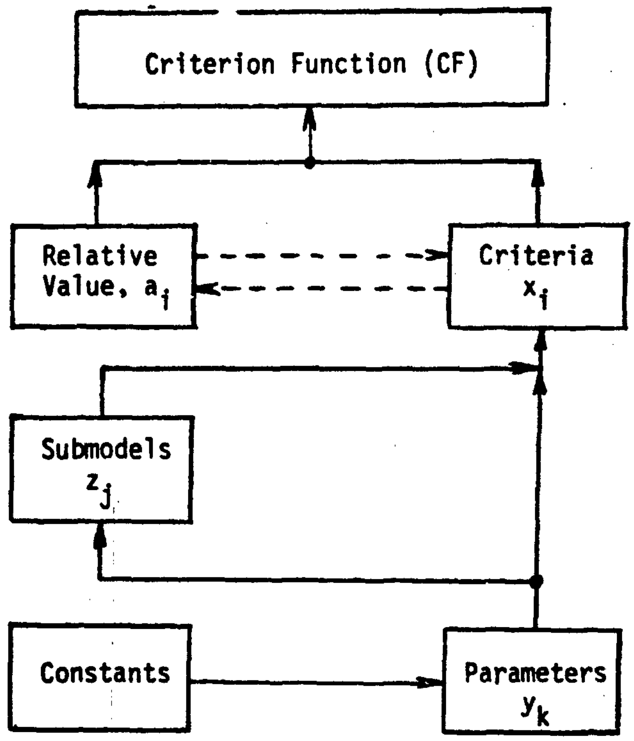

Figure 3.7 Criterion Function Constituents

Furthermore, the set of parameters $\{y_k\}$ can be related to the set of criteria defined for the evaluation. This usually requires mathematical modeling and results in quantitative relationships between the criteria, the parameters, and the submodels. Note that "the accuracy of these relationships is a direct function of the knowledge available from past experience, mathematical capability, the literature in the area, and current investigation and testing" [14, page 98].

Thus, $x_i = f_i\{z_j\}$ (2)

and since: $z_j = g_j\{y_k\}$ (3)

then: $x_i = f_i\{g_j\{y_k\}\}$ (4)

Having completed the criterion modeling, the designer must determine the range or allowable spread of each parameter (Figure 3.8). A candidate system with values of parameters outside these ranges is not a feasible candidate; thus, careful consideration must be given to the determination of these ranges. Narrow ranges, for example, will exclude a number of candidate systems Ranges for submodels and for criteria can then be determined using mathematical models obtained earlier (Figures 3.9 and 3.10).

	y_k	$y_{k\ min}$	$y_{k\ max}$
y_1	Parameter 1	$y_{1\ min}$	$y_{1\ max}$
y_2	Parameter 2	$y_{2\ min}$	$y_{2\ max}$
.	.	.	.
.	.	.	.
y_m	Parameter m	$y_{m\ min}$	$y_{m\ max}$

Figure 3.8 Range of Parameters

x_i	z_y	z_{ij} min	z_{ij} max
x_1	z_{11}	z_{11} min	z_{11} max
	z_{12}	z_{12} min	z_{12} max
	.	.	.
	.	.	.
	.	.	.
	z_{in}	z_{in} min	z_{in} max
x_2	z_{21}	z_{21} min	z_{21} max
	z_{22}	z_{22} min	z_{22} max
	.	.	.
	.	.	.
	.	.	.
	z_{2n}	z_{2n} min	z_{2n} max
.	.	.	.
.	.	.	.
.	.	.	.
x_p	z_{p1}	z_{p1} min	z_{p1} max
	z_{p2}	z_{p2} min	z_{p2} max
	.	.	.
	.	.	.
	.	.	.
	z_{pn}	z_{pn} min	z_{pn} max

Figure 3.9 Range of Submodels

	x_i	$x_{i\,min}$	$x_{i\,max}$
x_1	Criterion 1	$x_{1\,min}$	$x_{1\,max}$
x_2	Criterion 2	$x_{2\,min}$	$x_{2\,max}$
.	.	.	.
.	.	.	.
.	.	.	.
x_p	Criterion p	$x_{p\,min}$	$x_{p\,max}$

Figure 3.10 Range of Criteria

Finally, the criteria must be combined into a function which can yield a single value indicating the performance of the candidate system on a cardinal scale. Probability theory can be used to synthesize the criteria function by mapping multiple criteria onto a single probability space [14, Appendix C]. This method:

1) Provides a means for assessing the completeness of the set of candidate systems in terms of the range of criterion performance. Thus, candidates which might not have been otherwise considered are revealed.

2) Assesses the magnitude of the criteria interactions that exist and have significant effects.

It has been shown that the criteria and their interactions can be mapped into a multivariate probability space and the resulting criteria function for candidate system α takes the following form:

$$CF_{\alpha} = \sum_{i=1}^{n} \delta_i \; a_i \; P(A_i) - \sum_{\substack{i \\ i \neq j}}^{n} \sum_{j}^{n} \delta_{ij} \; a_{ij} \; P(A_{ij})$$

$$+ \sum_{i}^{n} \sum_{\substack{j \\ i \neq j \\ j \neq k \\ i \neq k}}^{n} \sum_{k}^{n} \delta_{ijk} \; a_{ijk} \; P(A_{ijk})$$

$$- \; . \; . \; . \; \pm \sum_{i}^{n} \sum_{\substack{j \\ i \neq j \\ \cdot \\ \cdot \\ \cdot \\ J \neq J+1}}^{n} \sum_{J+1}^{n} \delta_{ijk...(J+1)} \; a_{ijk...(J+1)} \; P[A_{ijk...(J+1)}]$$

where

$X_i \equiv$ Criterion random variable

$x_i \equiv$ Value of criterion random variable with range

$$x_{imin} \leq x_i \leq x_{imax}$$

$A_i \equiv$ the event $(X_i < x_i, \; X_j < x_j)$

,

,

,

$A_{ijk...(J+1)} \equiv$ the event $(X_i < x_i, \; X_j < x_j \; ...$

$X_{J+1} < x_{J+1})$ where $J + 1 = n$

$\delta_i P(A_i)$ $\equiv$ Marginal distribution function of the i^{th} criterion.

$$\delta_i \equiv \begin{cases} 1, \text{ when } P(A_i) \text{ exists} \\ 0, \text{ when } P(A_i) \text{ does not exist} \end{cases}$$

$\delta_{ij}P(A_{ij})$ $\equiv$ joint probability or the first-order interaction of x_i and x_j

$$\delta_{ij} \equiv \begin{cases} 1, \text{ when } P(A_{ij}) \text{ exists} \\ 0, \text{ when } P(A_{ij}) \text{ does not exist} \end{cases}$$

$\delta_{ijk\ldots(J+1)}P[A_{ijk\ldots(J+1)}]$ $\equiv$ joint probability or the J^{th} order interaction of $x_i \ldots x_{(J+1)}$

$$\delta_{ijk\ldots(J+1)} \equiv \begin{cases} 1, \text{ when } P[A_{ijk\ldots(J+1)}] \text{ exists} \\ 0, \text{ when } P[A_{ijk\ldots(J+1)}] \text{ does not exist} \end{cases}$$

This equation defines the relative value of a candidate system in the interval [0,1] and includes both the relative importance a_i of the respective criterion x_i and the value of the probability density of the x_i. When the value of a candidate system's performance increases with the performance itself, the most desirable candidate system is the one which yields the highest value of CF. Furthermore, the problem of identifying additional candidate systems can be related to the problem of identifying a particular

value of CF within the design space and relating the respective x_i to their physical significance. To minimize the risks and uncertainties introduced by the designer's incomplete knowledge, the design space should be carefully analyzed and in this manner, the designer increases his understanding of the nature of the value structure and the manner in which it relates to the candidate systems. Analyzing the design space involves the following general types of analyses:

1) Sensitivity analysis

2) Compatibility analysis

3) Stability analysis

The sensitivity analysis identifies the rate of change of the criterion function CF_α to each of the parameters y_k and to each of the submodels z_j. This shows the nature of the change in the criteria function resulting from variations in the parameters, y_k, or the submodels, z_j, and permits the designer to understand better the nature of his design space, thus enabling more effective optimization to occur.

In contrast to sensitivity, the compatibility analysis identifies those parameters or submodels having the least effect on the total CF value. When changes become necessary during subsequent equipment development, they should

occur first in those areas which are least sensitive.

The stability analysis permits the designer to identify the limits of performance prior to system breakdown and requires an understanding of the nature of the effects upon the system of exceeding criterion limits. This type of comprehension of the design space, then, is necessary for the designer to adequately assess the subsequent choice of the optimal candidate, and is accomplished from study of the nature of criteria interactions and their meaning on the performance of the candidate system [14, page 128].

At this point, after a thorough study of each of sensitivity, compatibility, and stability, formal optimization can occur. For the set of candidate systems involved, two basic steps are involved. The first can be viewed as "optimization within the candidate system" and determines for each candidate system that combination of parameter values which provides the optimal value of the criterion function. The second process, "the optimization among candidate systems," is simply the candidate system having the "best value of the criteria function. Note that selection of the "best" value of CF does not necessarily give the "optimal" candidate unless the CF_{α} for the given candidate has been optimized for that

candidate ("optimization within") prior to "optimization among" candidates [14, page 134].

Serious constraints to the design space studies are: 1) the required level of mathematical sophistication, 2) extensive computer usage, and 3) limitations to accuracy resulting from practical considerations in the implementation.

Having selected the optimal candidate system, it is now necessary to reexamine the environment in which the system will operate to assure consistency between the future environment and the chosen system. Considerations include the nature of the socioeconomic environment and the system's rate of technological obsolescence. In general, this implies a reexamination of the problem formulation input-output matrix.

Next, attempts should be made to predict the performance of the optimal system, cost estimates should be prepared, and remedial action is taken if costs exceed the bounds defined in the needs analysis.

To verify these projections and estimates, the system and its elements are finally tested and evaluated to the extent practical at this time. The testing usually reveals areas in which the design can be simplified and the

system can be improved and when this occurs, iteration of all affected decisions must occur in order to be completely safe on subsequent decisions.

3.3 DETAIL DESIGN

The activities of the detail design are those necessary to develop and implement the optimal system selected in the preliminary design. The importance of the feasibility study and preliminary activities is emphasized by the fact that most of the resources are expanded in the implementation of the production-consumption phases. Therefore, "it is, in general, less costly.to make errors during the earlier phases of the design-planning process where the effort is primarily analytical than to make them during the detail activities after expenditure of time, effort, and usually, large amounts of money" [14, page 155].

The detail activities begin with the preparation for design which consists of the adequate review of all information and data to this point. The possible improvement of the knowledge discussed should be considered. For example, the functional relationships between the criteria and the parameters may warrant a reevaluation.

As for the particular detail activities to be performed, these vary with the type of system under

consideration. Most USAF systems, however, have similar types of decisions to be made and these include:

1) The design, according to the morphology, of the subsystems, components and parts that make up the total system. As the design progresses down through the various levels, the requirements become much more precise and better defined.

2) The listing of accurate and complete assembly instructions ranging from simple hardware elements to large-scale systems such as an aircraft. Tables and exploded views can be effectively used to provide instructions.

3) Experimental construction to look for possible refinements and/or major changes which must be made.

4) Cost projections for labor, materials, management, facilities, and the various support functions required to produce, distribute, operate, and retire the system.

5) The consideration of the different logistics functions which provide reinforcement in accomplishing primary system functions. The integrated logistics support elements are: maintainability and reliability, maintenance

plan, support and test equipment, supply support, transportation and handling, technical data, facilities, personnel and training, support resource funds, and support management information.

6) The development of an organization plan for the accomplishment of the tasks required to effectively meet the needs of the production-consumption cycle.

7) Production planning with such considerations as type of production (intermittent versus continuous), inventory control, forecasting, scheduling, assembly sequencing, plant layout, quality control and testing.

8) Operations planning to assure efficient implementation and support of the produced system. Logistics plays an important role in operations planning because "it provides for the proper integration of the diverse needs of each area of interest" [14, page 230].

When the detail design is completed, the technical performance of the developed system through its production-consumption cycle is predicted to ensure the satisfaction of the designer's original needs and the accomplishment of the necessary adjustments. Costs are once again

analyzed and an overall review is conducted to improve or simplify any facet of the system. Note that "important changes, when uncovered, should be considered in the standard procedures of design-planning changes and the affected steps iterated in the basic design. Often, however, when redesign will lead to major changes and the improvement will require more resources than can be effectively used on this system, the changes are kept for the next generation of design" [14, page 241].

4.0 HUMAN RESOURCES IN THE DESIGN CONTEXT

The study of human resources as they impact upon the design of a system is not a new undertaking, and the volume of literature published on the subject is overwhelming. The general discipline has come to be known variously as human factors engineering, or simply, human factors, biomechanics, engineering psychology, or ergonomics [11, page vii]. McCormick has stated in summary that human factors engineering can be considered the process of designing for human use [11, page 3]. At this point a more precise definition of the composition of human factors is in order.

4.1 DEFINITION

David Meister [12] has defined human factors as a general term with precise meaning determined by the context of its useage. First, he defined human factors as those elements which influence the efficiency with which people can use equipment to accomplish the functions of that equipment. Second, the term may refer to the number and type of personnel selected to run the system and how they function. Third, the term may be used to refer to the level of personnel performance necessary in using the equipment and the effect of that performance on other system elements or on overall system goals.

And finally, the term can be used to refer to the effect of the overall system upon its personnel elements [12, pages 5,6].

In other words, the human factors are not discrete concepts with simple and finite definitions; but rather, they comprise a broad discipline for examining man's position in the man-machine system. The basic concept of the man-machine system is a closed-loop relationship between the human and his equipment. Meister [12, page 9] defines the major elements of this system as equipment, environment, tasks, and personnel. Each of these in turn, consists of many subelements, each of which may influence the efficiency of the man-machine system. The human interface to this system is complex and requires management of the joint efforts of psychology and engineering if optimal design decisions are to result.

4.2 Background

Although the study of human resources in the design context is not a new phenomenon, the major impetus occurred during World War II [11, page 4; 12, page 10]. During this time the disciplines of industrial engineering and psychology corroborated on human factors research with a strong applications-orientation. The emergence of new high technology systems which imposed increasing

and specialized demands on personnel led to suggested ways of improving performance through improved system design [12, pages 16, 17].

The research psychologist and the engineer were thus thrust together by the exigency of the times. However, the need for direct continuing communication has become all the more necessary because design problems and their attendant solutions have increased in complexity apace with the technological explosion since World War II. Moreover, the corroboration of psychologist and engineer is a continuing process within a given system design program because design problems and solutions tend to change, sometimes markedly, as the iterative process of system development progresses (12, page 17]. The proper inclusion of human factors into the system design is dependent upon the availability of relevant quantifiable data as an input to the decision process.

The inclusion of human factors in system design has been the topic of a growing body of research in recent years (see [5], [15]). The thrust of the research has been at developing methods of accomodating a successful and standardized approach to the inclusion of human factors in system design. A basic philosophical schism between

the behavioralist and the scientist has led to continuing problems during practical applications while in theory the psychologist and engineer are in agreement on the necessity for their corroboration. Askren [5] summarized a number of studies which have as their aim the identification of a methodology for assuring the inclusion of human resources in the design process. He characterized the types of human resources data relevant to the design process as follows:

"A wide variety of human resources data were found to be useful as criteria in design studies. This included such factors as manpower quantity, technician skill level, technician job specialty, personnel dollar cost, type and amount of training, task performance time, job difficulty, and personnel turnover rate ... the type of data relevant to a particular design problem is a function of the nature of the design problem. All human resources data do not apply to all design studies. It is critical to provide the engineer with data that is most relevant" [5, page 9].

4.3 HUMAN RESOURCE CATEGORIES FOR DESIGN

For the purposes of the approach to the inclusion of human factors data into the design process, a system of human factors categories was necessary to provide

a reference for the collection of relevant data pertinent to anticipated design problems. During the analysis of the feasibility study for the design of a particular system, the human factors categories relevant to the design problem under consideration could be identified. This would, in turn, lead the designer to an appropriate entry point of the human factors data base where the data most relevant to the design problem would be available to the engineer.

In selecting a system of human factors categories it was felt that Meister's four categories [12] did not give a sufficiently detailed breakdown for this use. Robert Blanchard [7], on the other hand, identifies sixteen categories of human resources data. His types of data are identified according to the requirements of the users and with some modification became the basis of our thirteen human factors categories. A comparison of these thirteen categories with Meister's four categories is illustrated in Figure 4.1.

The following definitions of the individual categories come largely from Blanchard [7, pages 30, 31]:

HUMAN FACTOR CATEGORIES	MEISTER'S CATEGORIES			
	TASK	PERSONNEL	EQUIPMENT	ENVIRONMENT
1. HUMAN CAPABILITIES	X		X	
2. BEHAVIORAL CONSIDERATIONS	X	X		
3. PERSONNEL COST	X	X	X	
4. TRAINING LEVEL	X	X		
5. PERSONNEL PERFORMANCE	X			
6. TEAM PERFORMANCE	X			
7. MAN-MACHINE INTERFACE	X		X	
8. PERSONNEL BACKGROUND		X		
9. PERSONNEL READINESS		X		
10. PERSONNEL QUALIFICATIONS		X		
11. BASELINE DATA			X	
12. OPERATING ENVIRONMENT				X
13. EXTERNAL ENVIRONMENT				X

FIGURE 4.1 The Human Factor Cateogories Versus Meister's Classification

1. Human Capabilities: Human capabilities relate to the physiological as well as behavioral limitations of the individual. They illustrate the functional relations between the various human processes and the equipment and task parameters.

2. Behavioral Considerations: The behavioral considerations include such factors as personnel motivation, group dynamics, productivity, and job satisfaction, and relate to the outcome of personnel activities.

3. Personnel Cost: Personnel costs are a function of team size and composition, training level required to accomplish the task, and the level of associated indirect charges for overhead. While relating mostly to dollar costs, costs can also relate to time and equipment requirements.

4. Training Level: Training level relates to the formal and on-the-job training (OJT) for various personnel classes which allows them to reach the required performance levels on various personnel functions. The training level is a function of the tasks to be performed and the qualifications of the personnel.

5. Personnel Performance: Personnel performance relates to the accomplishment of the different tasks of the system. Standards are associated with critical personnel

activities for various systems. Achievement of standards should insure attaining a prescribed level of system performance.

6. <u>Team Performance</u>: Team performance is the set of activities specified by the designed system, the task to be performed, and the operating environment. It is a function of group interaction and integration, and evaluated against defined criteria.

7. <u>Man-Machine Interface</u>: Man-machine interface considers the relation between the human and a wide range of specific hardware components with various physical characteristics and human performance levels.

8. <u>Personnel Background</u>: Personnel background involves a relationship among such factors as educational levels, aptitude testing, and personnel skill level.

9. <u>Personnel Readiness</u>: Personnel readiness for various tasks on operating systems relates to performance levels and degrees of performance variability within and between people and teams.

10. <u>Personnel Qualifications</u>: Personnel qualifications include such factors as skill level, experience, and familiarity with the task to be performed.

11. <u>Baseline Data</u>: Equipment baseline data relates to

the measures of personnel performance on current systems and subsystems. This data is then used to match the equipment to the required task.

12. Operating Environment: Operating environmental considerations include such factors as temperature, illumination, noise, vibration, motion, and space limitations. Where possible, these factors are related to a physiological criterion such as hearing loss, visual attenuation, and nausea.

13. External Environment: External environmental factors are exogenous to the task being performed and include social, political, and economic considerations.

5.0 THE INCLUSION OF HUMAN FACTORS IN SYSTEM DESIGN

Now that the design methodology has been briefly defined and the human resources in the design context have been both defined and categorized, the task of demonstrating the integration of human factors into the design process can proceed. Although this discussion deals specifically with integration of human factors, the observation is made that the following methodology applies to the more generalized problem of insuring the inclusion of any relevant factor into a design or planning problem.

5.1 APPLICATION OF FEASIBILITY STUDY

The feasibility study was defined earlier in the context of the design methodology (Para. 3.3.1) and now a specific application of the methodology is developed. For this purpose it is assumed that a thorough and complete analysis of needs has been accomplished, and the process of identifying and formulating the problem is underway. The input-output matrix which will be developed to accomplish this task will of course, take into consideration all relevant factors bearing upon the successful satisfaction of the previously defined needs. Even for problems of limited scope, the development of a complete input-output matrix can become an extensive process

requiring the creativity and experience of experts knowledgeable in each of the relevant factors inherent in the specific design problem.

The input-output matrix provides a means for bounding the design problem through the specific identification of data which is necessary to describe subjectively the nature of the design space. This is accomplished by considering each of the phases of the production-consumption cycle and identifying as many descriptors as practical in a matrix, as shown in Figure 5.1. This data must be as specific and exhaustive as is possible, given the usual designer's dilemma of incomplete or imperfect knowledge in the arena of high technology design. The implication, therefore, is implicit that as additional knowledge relevant to the design problem is identified it should be added to the matrix. The matrix itself is divided into four categories to aid in organizing the data.

	Inputs		Outputs	
	Intended	Environmental	Desired	Undesired
Production				
Distribution				
Consumption-Operation				
Retirement				

Figure 5.1 The Input-Output Matrix

An effective approach to the matrix is to consider the outputs first. In general, these are definitive descriptors of the needs of the respective phases of the production-consumption cycle as they reflect the results of a completed and successful system development. Such descriptors of desirable characteristics describe the "desired output" category. However, when a system is developed there is inevitably associated with the outcome some undesirable characteristics which, if properly anticipated, can be minimized with regard to their effects on the outcome. These undesirable descriptors are the "undesired output" category. Care should be taken, however, to avoid listing opposite effect descriptors as they do not contribute meaningfully to the solutions.

"Environmental inputs" are those characteristics or tangibles that are available or that influence the designer. They constitute the existing conditions, facilities, equipment, and personnel that are ingredients, and they contribute to producing the outputs. Note that "influence" does not necessarily mean a positive influence: it could detract from the effort to achieve results.

Once the environmental inputs have been defined for each phase of the production-consumption cycle, the final matrix category, the "intended inputs," can be

derived by answering the question: "What is needed to supplement the environmental inputs in order to achieve the outputs?" When this has been applied to each phase in the production-consumption cycle, a good list of "start-up" considerations is available for the system. The intended inputs then start the process to enable the achievement of outputs.

The question of "adequacy" of an input-output analysis will vary from project to project and must be judged by the designer. The characteristic that remains consistent among all projects is the inability to define all requirements to a satisfactory level without considerably more information than is normally available at this point in the project. However, it is important to the designer that each cell in the matrix be as complete as possible. Doing so raises questions which help direct attention to the nature of the problems to be solved before successfully meeting the requirements of that particular cell and, this sets the stage for future decisions.

The input-output matrix helps to bound the problem which tends to direct the thinking necessary to accomplish requirements of the defined needs. The design process now shifts to a synthesizing mode requiring the identification of functions, which when pieced together, will provide a solution tailored to the need. The

synthesis of solutions involves the identification of candidate systems which would accomplish every function and activity related to the total system if the candidate system were completely developed. The designer is charged with the task of synthesizing a set of candidate systems bearing in mind that the larger the number of candidate systems for a given set of criteria and constraints, the greater the likelihood of emerging with the "best" possible system to meet the defined needs. Before proceeding with preliminary design activities, however, an examination of this set of candidates must be made to assure that these potential systems will be feasible. A screening of candidate systems is necessary. However, "no candidate system should be eliminated during the feasibility study unless that candidate cannot be physically assembled (for a certainty) and cannot meet the economic and financial limitations imposed by the input-output analysis of the problem identification and by the needs analysis" [14, page 55].

5.2 AN INPUT-OUTPUT MATRIX FOR AIR FORCE SYSTEM DESIGN

The crux of the problem of demonstrating the integration of human factors into the design process then is the development of an input-output matrix relating to Air Force needs. The input-output matrix developed follows the production-consumption cycle which was defined by the design morphology and which was earlier

related to the Air Force system life cycle phases. This provides continuity and consistency with Air Force design philosophy. However, these four phases (i.e., production, distribution, oper.tions, and retirement) provide a very coarse division of the matrix and provide a severe limitation on its practical usefulness and manageability. Therefore, a further division of each phase has been developed to identify the key elements of each phase of the system life cycle (Figures 5.2, 5.3, 5.4, 5.5) The elements vary from phase to phase and are tailored to the objectives of the particular phase. These elements are specifically defined in terms of the phase with which they are associated. For a definition of the elements by phase, see Appendix A.

5.3 ILLUSTRATED INPUT-OUTPUT MATRIX - DEMONSTRATING THE INCLUSION OF HUMAN FACTORS IN SYSTEM DESIGN

The demonstration of the application of an input-output matrix is limited to establish realistic bounds upon the scope of this discussion. The demonstration has been restricted to the development of one element from each phase of the matrix. In addition, the development of the input-output matrix will be generalized, that is, a specific system will not be modeled, but the matrix will rather demonstrate the inclusion of design factors (descriptors) typically relevant to aerospace system design.

PHASE	ELEMENTS	INPUTS INTENDED	INPUTS ENVIRONMENTAL	OUTPUTS DESIRED	OUTPUTS UNDESIRED
PRODUCTION	PRODUCTION PLANNING				
	PRODUCTION CONTROL				
	SUPPLY SUPPORT				
	COSTS				
	FACILITIES				
	TEST AND SUPPORT EQUIPMENT				
	RELIABILITY/MAINTAINABILITY /AVAILABILITY				
	ORGANIZATION PLAN				
	PERSONNEL AND TRAINING				
	TRANSPORTATION & HANDLING				
	TECHNICAL DATA				
	TESTING				
	QUALITY ASSURANCE				
	MANAGEMENT INFORMATION				
	ENVIRONMENTAL				

Figure 5.2 Input-Output Matrix for Aerospace System Design - Production

PHASE	ELEMENTS	INPUTS		OUTPUTS	
		INTENDED	ENVIRONMENTAL	DESIRED	UNDESIRED
DISTRIBUTION	DISTRIBUTION PLANNING COSTS ORGANIZATION PLAN PERSONNEL AND TRAINING TRANSPORTATION AND HANDLING USER'S TRAINING MANAGEMENT INFORMATION				

Figure 5.3 Input-Output Matrix for Aerospace System Design - Distribution

PHASE	ELEMENTS	INPUTS		OUTPUTS	
		INTENDED	ENVIRONMENTAL	DESIRED	UNDESIRED
O P E R A T I O N S	OPERATIONS PLANNING PERFORMANCE SUPPLY SUPPORT MAINTENANCE PLANNING COSTS FACILITIES TEST AND SUPPORT EQUIPMENT RELIABILITY/MAINTAINABILITY /AVAILABILITY ORGANIZATION PLAN PERSONNEL AND TRAINING TECHNICAL DATA SAFETY				

Figure 5.4 Input-Output Matrix for Aerospace System Design - Operations

PHASE	ELEMENTS	INPUTS		OUTPUTS	
		INTENDED	ENVIRONMENTAL	DESIRED	UNDESIRED
RETIREMENT	FUTURE DEMAND SUPPLY SUPPORT MAINTENANCE PLANNING COSTS FACILITIES TEST AND SUPPORT EQUIPMENT ORGANIZATION PLAN PERSONNEL AND TRAINING TRANSPORTATION AND HANDLING SAFETY MANAGEMENT INFORMATION ENVIRONMENTAL				

Figure 5.5 Input-Output Matrix for Aerospace System Design - Retirement

Because a concomitant problem of including human factors in design has consistently been one of the availability of a human factors data base [7], an attempt has been made to reference the descriptors of the matrix which relate to human factors to the previously mentioned human factors/design bibliography [15]. This demonstrates the flexibility of the matrix as a tool of the designer to interface with a relevant data dase. The cross-referencing of the matrix with the data base is accomplished through the footnoting of the appropriate descriptor in a manner which corresponds to a reference or group of references in the data base.

Appendix B is an adaptation of the previously reported bibliography on the morphology of design with the inclusion of human factors [15]. The appendix illustrates a data base of human factors literature of interest to systems designers. It represents an initial effort aimed at demonstrating the feasibility of bridging the communications gap between the systems design engineer and the human factors specialist. This effort is limited to the extent necessary to accomplish this goal. A data base in some form is necessary if the design engineer is to include relevant criteria into the design analysis to insure adequate consideration of the inclusion of human factors in system design.

The demonstration data base uses the previously defined thirteen human factors categories (see Para. 4.3) to catalog the human factors references from the bibliography. The individual references which pertain to human factors are sorted with regard to the human factor category or categories to which they refer. The thirteen groups of references are then numbered to facilitate access. For example, a reference number of 7.0 refers to all the references listed in human factors category number seven (Man-Machine Interface), while a reference number of 7.2 refers specifically to article number two (2) in category number seven (7). Multiple footnoting utilizing these reference numbers are often required to adequately relate a particular matrix descriptor to the data base.

Figures 5.6, 5.7, 5.8, and 5.9 are the illustrated input-output matrices. It can be readily seen from these generalized examples that the completion of a full set of matrices for an actual system under development is a formidable task. But the payoffs, both in terms of optimal system performance and system life cycle costs, more than justify the effort. A criterion, once identified, can be readily included in the design analysis. But of greater importance during the initial stages of system design is the identification of those factors which are the unknowns or unquantified factors which

Phase	Elements	Intended	Environmental	Desired	Undesired
PRODUCTION	•Production Planning •Production Control •Supply Support •Costs				
	•Facilities	•Frequency and Duration of Production Runs •Capital Equipment Analysis •Adequate Warehouse Space •Adequate Layout Planning (Job Design)-(5, 7, 7.29, 11, 12) •Adequate Location Planning •Adequate Capacity Planning	•Political Realities (13) •Year-Round Usage (Climatic) •Controlled Environment (5, 12) •Existing Unused Facilities •Available Skilled Workforce (4, 10, 10.5) •Available Raw Materials •Proximity to Suppliers •Zoning Restrictions •Available Transportation Network •Real Estate Expense •Pollution Standards •Personnel Enemities (2, 2.6, 2.7, 3) •OSHA Requirements (12, 13) •Utilities Available	•Utilization of Existing Facilities •Minimization of New Investments •Optimal Workforce (3, 3.3, 3.6, 5, 6, 10, 10.3, 10.5) •Economical Energy •Proximity to Suppliers •Adequate Supply of Raw Materials •Economical Reliable Production	•Inefficient Design of Facilities •Dangerous Effluents (12,13) •Delayed Availability of Facilities
	•Test and Support Equipment •Reliability/Maintainability/Availability •Organizational Plan •Personnel and Training •Transportation and Handling •Technical Data •Testing •Quality Assurance •Management Information •Environmental				

Figure 5.6 Illustrated Input-Output Matrix · Production

Phase	Elements	Intended	Environmental	Desired	Undesired
DISTRIBUTION	• DISTRIBUTION PLANNING • COSTS • ORGANIZATION PLAN • PERSONNEL AND TRAINING				
	• TRANSPORTATION AND HANDLING	• TRANSPORTATION AND PLANNING TECHNIQUES • QUALITY CONTROL (3, 4, 5, 5.3, 5.4, 5.7, 5.10) • EFFICIENT TRANSPORTATION METHODS (COST EFFECTIVE PACKAGING)	• ENVIRONMENTAL FACTORS (1, 1.32, 1.35, 1.54, 12, 13) • AVAILABLE MODES OF TRANSPORTATION • TRANSPORTATION LEGISLATION • SCHEDULE OF PRODUCTION OUTPUTS	• MINIMUM TRANSPORTATION COST • MINIMUM HANDLING COST (1) • MINIMUM PERSONNEL COST (2)	• EXCESSIVE BREAKAGE • DELIVERY DELAYS
	• USER'S TRAINING • MANAGEMENT INFORMATION				

Figure 5.7 Illustrated Input-Output Matrix - Distribution

PHASE	ELEMENTS	INTENDED	ENVIRONMENTAL	DESIRED	UNDESIRED
OPERATIONS	•OPERATIONS PLANNING •PERFORMANCE •SUPPLY SUPPORT				
	•MAINTENANCE PLANNING	•MAINTAINABILITY ANALYSIS (3, 7, 7.2, 7.47, 11) •PERSONNEL REQUIREMENTS ANALYSIS (3, 3.6, 3.13, 4, 5, 5.8, 5.16, 5.17, 6, 10, 10.3, 10.5) •PROJECTION OF TRAINING PROGRAMS, SKILLS, EQUIPMENT, TOOL AVAILABILITY, AND FACILITIES (4, 5, 6, 11)	•MAINTAINABILITY REQUIREMENTS (3, 7, 11) •OPERATIONAL REQUIREMENTS (1, 7, 11) •STANDARD TOOLS AND EQUIPMENT (5, 6, 7, 7.10, 11) •AVAILABLE PERSONNEL SKILLS (10) •LIFE CYCLE COSTS (3, 11) •ENVIRONMENTAL CONDITIONS (1, 1.20, 1.32, 12, 12.29, 13)	•REDUCED FREQUENCY OF MAINTENANCE ACTIVITIES (3, 7, 11) •REDUCED MAINTENANCE DOWNTIME •LIMITED MAINTENANCE PERSONNEL REQUIREMENTS (3, 3.14, 4, 5, 5.8, 5.15, 11)	•MAINTENANCE COMPLEXITY (1, 1.37, 3, 3.7, 5, 5.15, 7, 10, 11) •HIGH MAINTENANCE COSTS (3, 7, 11) •MAINTENANCE ERRORS (1, 1.21, 1.22, 2, 9)
	•COSTS •FACILITIES •TEST AND SUPPORT EQUIPMENT •RELIABILITY/MAINTAINABILITY/AVAILABILITY •ORGANIZATION PLAN •PERSONNEL AND TRAINING •TECHNICAL DATA •SAFETY •MANAGEMENT INFORMATION •ENVIRONMENTAL				

FIGURE 5.9 ILLUSTRATED INPUT-OUTPUT MATRIX - OPERATIONS

PHASE	ELEMENTS	INTENDED	ENVIRONMENTAL	DESIRED	UNDESIRED
RETIREMENT	•FUTURE DEMAND •SUPPLY SUPPORT •MAINTENANCE PLANNING •COSTS •FACILITIES •TEST AND SUPPORT EQUIPMENT •ORGANIZATION PLAN				
	•PERSONNEL AND TRAINING	•TRAINING PROGRAMS (4, 4.5, 4.10, 4.11, 8, 10, 10.8) •PERSONNEL MOTIVATION (2, 9)	•EMPLOYEE COMPENSATION LAWS (2, 3, 13) •MAINTENANCE REQUIREMENTS (4, 4.14, 10) •FUTURE DEMAND PLANS (3, 4, 11)	•ORDERLY ATTRITION OF PERSONNEL (2, 3) •LOW COST TRAINING PROGRAMS (3, 4) •LOW PERSONNEL COSTS (3)	•OBSOLESCENCE OF SKILLS (4, 5, 10, 10.6) •UNMOTIVATED PERSONNEL (2,9)
	•TRANSPORTATION AND HANDLING •SAFETY •MANAGEMENT INFORMATION •ENVIRONMENTAL				

FIGURE 5.9 ILLUSTRATED INPUT-OUTPUT MATRIX - RETIREMENT

must be resolved before the system design problem can be successfully solved.

6.0 CLARIFICATION OF OBJECTIVE AND SUBJECTIVE INPUTS TO DESIGN DECISIONS

During the development of a system it becomes very apparent that objectivity is necessary to the achievement of effectiveness. The need to evaluate and to compare performance of alternatives requires in-depth consideration of the many facets of the design, usually in such a way that trade-offs between subjective and objective requirements become necessary. For example, it is well known that air crew comfort must be considered in the development of an aircraft in order to achieve efficient crew performance. Lack of environmental comfort for a pilot is a major contributor to fatigue and other undesirable traits that lead to rapid deterioration of pilot judgement - a vital input to mission effectiveness. Consequently the designer is faced with the problem of clearly identifying the system's needs in such a way that the important characteristics of the candidate systems are consistently related to the criteria defined. In the identification of these characteristics the assessment of many areas will require estimating the effects of relatively subjective inputs. When the decision is made that this measurement is important enough to spend resources on the problem, then models are constructed to estimate the values and

testing occurs to verify relationships.

Hence, it becomes apparent that the designer has a requirement to clearly identify the subjective and objective inputs to his decisions, particularly in the choice of the optimal candidate system. Figure 3.5 is an attempt to have the designer identify those elements that contribute to the meaning or to the measurement of each criterion. Here the designer lists any attribute or characteristic (whether subjective or objective) that is important to the estimation of that criterion in a quantitative manner. In subsequently attempting to synthesize mathematical formulations for the criterion, the designer comes to grips with the problems of evaluation of these elements. Criterion elements that are readily measured or estimated present little difficulty to the designer, and classically, these form the larger proportion of the technical constituency of USAF systems. Those elements that are subjective, however, provide the designer with the following dilemma. Are they of sufficient importance to include in the evaluation of the criterion <u>along with the objective input</u>? If they are, then methods must be devised for:

1) estimating their effects in a manner comparable to the more objective inputs, and

2) including the resulting effects in a criterion function which can be integrated into a multiple criteria function (i.e. criteria function).

If these are not of sufficient importance, then their effects are used to assess performance of the optimal candidate system after it has been defined, usually having little or no influence on its choice.

While the effects of modeling subjective elements of the criteria are clearly observed, there are similar considerations occurring throughout the entire morphology. In general the subjectivity is included more readily during the needs analysis, problem identification, synthesis of solutions, and the screening activities since the designer has the basic problem of establishing as large a base of candidate systems as possible. Hence, the subjectivity (and to some extent the objectivity) act as guidelines for the development of the candidate systems that will emerge from the feasibility study.

During the preliminary activities the designer comes to grips with the subjectivity by making explicit (in the form of a criteria function) those submodels and parameters to be included in the formal optimization. It is here, then, that the critical decisions are made in the overall design of the system. and hence, it is

here in the preliminary activities that the "soft" areas contributing to the design criteria must be included. The problems of inclusion are those that have been avoided to a large extent by designers since these problems usually involve the activities furthest removed from what is considered as the "mainstream" of the equipment design and development. Consequently, major contributions to the effective inclusion of subjective (and other "soft") inputs can be made by identifying procedures (and even algorithms in some cases) for the estimation of the effects of these elements. In many cases, the effects of human factors are considered "subjective" by equipment designers and hence, have the difficulties described herein, and can be approached effectively as described above.

The development of the plans that constitute the detail activities include the entire spectrum of considerations provided by the knowledge in the disciplines relating to a given system. Included in all major USAF systems are those subsumed along with other areas of system support. Several major USAF attempts to integrate these disciplines have occurred in the past few decades (i.e. System Engineering and System Management documentation), but in almost every case, true integration of human factors occurred where the need was clearly

shown from recent history, and where clear procedures were defined.

More recently DOD implemented procedures for integrating logistics support during the entire life cycle of a system. While philosophically accurate, the problems of procurement and practice often eliminated the advantages to USAF of an integrated support system. Consequently, the political and economic ramifications become crucial to the acceptance of any methods put forth to enhance system development. This is a clear indication that in some cases these "soft" areas should be modeled for their effects on the criteria function.

Consequently, an attempt should be made to develop several criterion functions showing the inclusion of human factors elements along with the disciplinary inputs into the emerging function. The method shown in the text [14, Appendix C] provides the mathematical logic for the development.

7.0 CONCLUSIONS

This research has achieved its stated purpose of clarifying a design morphology which is applicable to large scale systems in general, and to USAF systems in particular, while demonstrating the inclusion of human factors in system design. The specific conclusions which have been identified are discussed below.

7.1 APPLICABILITY OF DESIGN MORPHOLOGY TO AEROSPACE SYSTEMS

The design morphology described herein is applicable to aerospace systems and is compatible with the life cycle phases currently used by DOD. A direct comparison between the USAF life cycle and that of the design morphology indicated a one-to-one correspondence between the phases. Moreover, the design morphology represents a comprehensive philosophy for system design and is therefore applicable to a full range of design problems including large scale aerospace systems.

7.2 VALUE OF DESIGN MORPHOLOGY

The design morphology provides an orderly and rational sequence of decisions requiring resolution to design and develop the optimal system for DOD requirements or other defined needs. The three design phases - feasibility study, preliminary design, and detail design -

consist of a number of sequential activities which ensure a complete and thorough approach to the solution of the problem.

7.3 COMMUNICATION BETWEEN DESIGNERS AND HUMAN FACTORS SPECIALISTS

There appears to be a significant communication problem between the DOD equipment design community and the human factors specialists (as demonstrated by the references) although there is general agreement on the necessity for their corroboration. The corroboration of psychologist and engineer is a continuing process within a given system design program. The proper inclusion of human factors into the system design is dependent upon the availability of relevant quantifiable data as an input to the decision process.

7.4 THREE DIMENSIONAL MATRIX

The concept of a three dimensional relationship among human factors, the design steps, and the current literature is an effective approach to the solution of the problem of human factors inclusion into the design morphology. The translation of this relationship to a conceptualized matrix provides a rational and straightforward method for the complete identification of relevant human factors and for their inclusion into the design process.

7.5 HUMAN FACTORS IDENTIFICATION AND CLASSIFICATION

Additional effort is required to identify and classify the human factors relevant to the design of aerospace systems. For the purpose of the inclusion of human factors data into the design process a system of human factors categories was found to be necessary to provide a reference for the collection of relevant data pertinent to anticipated design problems. Such a system of categories was devised and its use illustrated.

7.6 HUMAN FACTORS REFERENCE BASE

An effort should be initiated to maintain a complete human factors reference base along the lines illustrated by Appendix B. The data base should be standardized, validated, and made available to DOD agencies and contractors. Moreover, the data base must, to the maximum extent possible, represent quantified empirical data which should be standardized to facilitate engineering useage.

7.7 INPUT-OUTPUT MATRIX

The input-output matrix provides a means for bounding the design problem through the specific identification

of characteristics which are necessary to describe the nature of the design space. By bounding the design problem the input-output matrix helps to direct the analysis necessary to accomplish requirements of the defined needs. The importance of this approach warrants further study of the matrix and its phase elements in the context of aerospace system design.

7.8 SUBJECTIVE DESIGN INPUTS

The need for defining means for estimating the effects of human factors and other subjective inputs on the design optimization process was reinforced by this research. It was shown that these subjective inputs should be modeled for their effects on the criteria function. Therefore an attempt should be made to estimate their effects in a manner comparable to the more objective inputs.

8.0 DEFINITION OF POTENTIAL AREAS FOR FUTURE INVESTIGATION

The research for fiscal year 1978 is planned to augment the current activities by pursuing in additional depth the design morphology with emphasis on human factors. For the coming year,* an illustrative hardware system will be selected and attempts made to develop the input-output matrix, identify formal system criteria, estimate the significance of criterion interactions, develop criteria-parameter relationships and structure a criteria function. While this research clarifies the basic design methodology, there were several areas that emerged from the current research that appear to justify further investigation. These are suggested below.

8.1 CONTINUED DEVELOPMENT OF RELATIONSHIPS AMONG HUMAN FACTORS, DESIGN MORPHOLOGY, AND THE EXISTING LITERATURE

The current research established the beginnings of a formal three dimensional relationship among human factors, the steps in the design morphology, and the existing literature. This was accomplished by formally

* "Augmentation of Research Into Morphology of Design of Aerospace System" Proposal Submitted to AFOSR by University of Houston, February 15, 1977.

defining the major (or basic) categories of human factors as they related to each step in the design morphology. Then each major publication in the current literature as shown in this research [15] was related to the respective human factors-design step pair. The volume of effort required to complete this research was beyond the scope of the resources provided, hence this should be continued in order to provide more complete coverage for future research and application.

8.2 STUDY OF CURRENT DOD/USAF POLICY FOR DESIGN OF TECHNOLOGICAL SYSTEMS FOR POTENTIAL MODIFICATION TO ENHANCE INCLUSION OF HUMAN FACTORS FROM MORPHOLOGICAL CONSIDERATIONS

DOD has a proliferation of systems engineering/systems management documentation including regulations, circulars, specifications, standards, etc. which require specific actions to assure compliance by the developing organization. These should be reviewed to assure USAF of an efficient compendium of requirements, and to ascertain that all decisions made relative to hardware and/or system development efficiently relate to human capabilities. The design morphology provides an excellent standard by which to assure the inclusion of all major development decisions.

8.3 SUPPLEMENTARY ANALYTICAL THEORY DEVELOPMENT

The development of criteria, submodels, and parameters, as indicated lead to a multidimensional space referred to variously as a "hyperspace," "design space," and "multivariate space." While the conceptual theory for the structure of this space is relatively complete, there exists certain practical aspects which merit development in addition to the resources currently provided. Such problems as mapping a polynomial into a probability space, multivariate goodness-of-fit tests, elaboration of the parametric relationships resulting from the multivariate interactions, and many more should be developed. Clarification of these areas could have significant influence on improvement of reliability/maintainability engineering, as well as the more classical problem of system development. More importantly, however, these areas will permit more readily acceptable means for integrating human factor decisions into the design process, particularly in the system optimization decisions.

8.4 CONTINUE DEVELOPMENT OF INPUT-OUTPUT MATRIX

Effort should be devoted to continue the development of the input-output matrix for all elements of the production consumption cycle. This work would provide a source of information to the USAF designer

for completeness of planning considerations.

8.5 DATA BASE DEVELOPMENT FOR HUMAN FACTORS

Additional study should be made to assure inclusion of human factors metrics into a generalized data base. This activity will identify classes of data elements necessary to the validation of human factor adequacy, identifying specific elements of each class. The data elements must, to the maximum extent possible, represent quantified empirical data translated into a standardized data format. The level of effort required for human factors data base development is beyond the scope of the resources provided. However, the long term solution to the problem of the proper inclusion of human factors in system design will inevitably return to the availability of human factors metrics, hence further research is necessary.

8.6 CONTINUED DEVELOPMENT OF THE DESIGN/HUMAN FACTORS REFERENCES

The work illustrated in Appendix B should be continued to provide a more complete design reference list for each given human factor. Further specific attempts should be made to identify data elements of interest to a given class of equipment for each human factor in a given stage of the design morphology.

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APPENDIX A

DEFINITIONS OF ELEMENTS

This appendix provides working definitions for the elements of the individual life cycle phases of the input-output matrix for Air Force system design.

PRODUCTION PHASE

ELEMENTS:

- PRODUCTION PLANNING
- PRODUCTION CONTROL
- SUPPLY SUPPORT
- COSTS
- FACILITIES
- TEST AND SUPPORT EQUIPMENT
- RELIABILITY/MAINTAINABILITY/AVAILABILITY
- ORGANIZATION PLAN
- PERSONNEL AND TRAINING
- TRANSPORTATION AND HANDLING
- TECHNICAL DATA
- TESTING
- QUALITY ASSURANCE
- MANAGEMENT INFORMATION
- ENVIRONMENTAL

PRODUCTION PLANNING:

The major considerations in production planning include the type of production (continuous versus intermittent), the plant layout, the sequence of assembly, the production rate, the use of hiring, firing, and overtime, the inventory levels, and the scheduling of the production activities.

PRODUCTION CONTROL:

Production control consists of a control plan which adjusts production and inventory levels, a feedback system which allows for correction of errors, and the use of network scheduling techniques to monitor the critical activities.

SUPPLY SUPPORT:

Supply support for the production process consists of all raw materials and components (units, assemblies, modules, etc.), repair parts, consumables, special supplies and related inventories needed to produce a finished product, test and support equipment, facilities, and training equipment. Considerations include each production level and each location where conponent parts are distributed and stocked, the distances between stockage points, and the methods of material distribution [6, page 8].

COSTS:

The cost analysis involves the costs of production as well as those of all the elements considered in the production

phase. The definition of cost categroies should be consistent with the requirements of the USAF and the ability to evaluate system performance against criteria resulting from system requirements.

FACILITIES:

Production facilities include the physical plant, real estate, temporary structures, housing, intermediate shops, depots, etc. requried to support manufacturing and production testing of the system, storage for materials and subassembly components, and training operations. Capital equipment and utilities (heat power, air conditioning, telephone, etc.) are considered as part of facilities [6, page 9].

TEST AND SUPPORT EQUIPMENT:

Test and support equipment used in production includes all tools, monitoring and checkout equipment, metrology and claibration equipment, work stands and handling equipment required to support production activities associated with the system. This covers external test equipment and built-in test (BIT) equipment which is considered to be part of the system. Test and support equipment can be classified as "reculiar" (newly designed and/or off-the-shelf items peculiar to the system under development) or "standard" (existing items already in the inventory).

RELIABILITY/MAINTAINABILITY/AVAILABILITY:

These three concepts in the production phase relate to the production equipment as well as the support and test equipment. Reliability is the ability to perform the intended functions in the intended environment for as long as planned. This is often modeled by a probability density to estimate the probability of a failure. Numerical reliability requirements are derived on theoretical grounds by considering the performance requirements as well as the characteristics of the interfacing systems. Moreover, reliability performance predictions must be apportioned to the constituent elements within the system [14, page 176]. Maintainability is the ability of the system to be maintained in its intended environment. It is defined as the probability that a failed system is restored to operable condition in a specified environment. Maintainability analysis translates maintenance planning into detailed quantitative and qualitative requirements and affects the related elements for maintaining the system by estimating the liklihood of task accomplishment in the operational environment. It involves the allocation of the quantitative requriements to all levels of the system [14, page 170]. Availability is an

attribute that is a function of both reliability and maintainability, and a major factor in the planning for number of required units to accomp' sh operational goals [14, page 180].

ORGANIZATION PLAN:

The organization plan for production develops an organizational structure for the accomplishment of the tasks required during the production pahse and the activities required to achieve this organization in a timely manner.

PERSONNEL AND TRAINING:

Personnel and training considerations for production include the identification and programming of skills, number of people, and training needed to accomplish the activities of the production phase [14, page 228].

TRANSPORTATION AND HANDLING:

The transportation and handling needs of the production phase include special provisions, reusable containers, and supplies necessary to support packaging, preservation, storage, handling, and/or transportation of the primary system itself, its test and support equipment, components and subassemblies, personnel, techrical data, and facilities [6, page 9].

TECHNICAL DATA:

Technical data utilized in production includes drawings, microfilm, operating and maintenance instructions, modification instructions, provisioning and facilities information, specifications, inspection and calibration procedures, and computer software required to support installation and checkout of the system and associated test and support equipment [6, page 9].

TESTING:

Production testing consists of a sampling plan wherein the test verifies some particular physical characteristics of performance. The purpose is to verify compatibility among the constituent components as well as adequate technical performance [14, page 151].

QUALITY ASSURANCE:

Production quality assurance relates to the establishment of a standard of performance for a production process to provide the desired level of quality for the system. Statistical quality assurance consists of both process

control sampling and product acceptance sampling.

MANAGEMENT INFORMATION:

The management of production information consists of assembling data into a manageable aggregate for evaluation. It provides the feedback to the designer and to the producer as well as to the user from the system concerning conditions about the state of production activities. It also usually requires some formatting and analysis [14, page 232].

ENVIRONMENTAL:

Environmental considerations in the production phase include inputs such as social systems and available technologies, as well as outputs such as the product and production facilities, equipment, and personnel, the economic impacts, and the noneconomic effects [13, Chapter 12].

DISTRIBUTION PHASE

ELEMENTS:

- DISTRIBUTION PLANNING
- COSTS
- ORGANIZATION PLAN
- PERSONNEL AND TRAINING
- TRANSPORTATION AND HANDLING
- USER'S TRAINING
- MANAGEMENT INFORMATION

DISTRIBUTION PLANNING:

Distribution planning describes the activities for the adequate transfer of the system to the ultimate operator or consumer. It includes the various types of facilities, equipment, packaging, warehousing, promotional activities, shelf life, organiz tion, and individuals.

COSTS:

The cost analysis involves the direct and indirect costs of distribution as well as those of all the elements considered in the distribution phase. As in production, the definition of cost categories should be consistent with the requirements of USAF and the ability to evaluate system performance against criteria resulting from system requirements.

ORGANIZATION PLAN:

The organization plan for distribution develops an organizational structure for the accomplishment of the tasks required during the distribution phase.

PERSONNEL AND TRAINING:

Personnel and training considerations for distribution include the identification and programming of skills, number of people, and training needed to accomplish the activities of the distribution phase [14, page 228].

TRANSPORTATION AND HANDLING:

The transportation and handling needs of the distribution phase include special provisions, reusable containers, and supplies necessary to support packaging, preservation, storage, handling and/or transportation of the primary system, test and support equipment, spare/repair parts, personnel, technical data, and facilities [6, page 9].

USER TRAINING:

User training is an important consideration in the distribution phase. It involves getting the user familiar with the technical data, the operation of the system, maintenance instructions, conducting training seminars, and clearly defining the critical logistics activities.

MANAGEMENT INFORMATION:

The management of information related to distribution consists of assembling data into a manageable aggregate for user evaluation. It provides the feedback to the designer as well as to the user of the system concerning conditions about the state of distribution activities. Also, it usually requires some formatting and analysis [14, page 232].

OPERATIONS PHASE

ELEMENTS:

- OPERATIONS PLANNING
- PERFORMANCE
- SUPPLY SUPPORT
- MAINTENANCE PALNNING
- COSTS
- FACILITIES
- TEST AND SUPPORT EQUIPMENT
- RELIABILITY/MAINTAINABILITY/AVAILABILITY
- ORGANIZATION PLAN
- PERSONNEL AND TRAINING
- TECHNICAL DATA
- SAFETY
- MANAGEMENT INFORMATION
- ENVIRONMENTAL

OPERATIONS PLANNING:

Operations planning consists of the planning to accomplish on a timely basis all the basic elements of the operations phase. The planning should include the entire time spectrum of the system operating life and may be divided into long-range, intermediate-range, and short-range planning, usually involving feedback and control to sustain the required level of performance.

PERFORMANCE:

The performance of a system is measured by its ability to meet operational criteria and operational demands or needs within a given time when operated under specified conditions.

SUPPLY SUPPORT:

The supply support for operations consists of the planning and activity to provide and sustain all repairable spares (units, assemblies, modules, etc.), repair parts, consumables, special supplies and related inventories needed to support scheduled and unscheduled maintenance actions associated with the operation of the prime equipment, test and support equipment, facilities and training equipment. Considerations include each maintenance level and each geographical location where spare/repair parts are distributed and stocked, the distances between stockage points, and the methods of material distribution [6, page 8].

MAINTENANCE PLANNING:

Maintenance planning for operations is the activity that

identifies the support requirements and plans for maintenance in order to satisfy operational goals. Concepts and requirements for each level of equipment maintenance to be performed are established. A maintenance engineering analysis is usually accomplished during concept formulation and provides the basis for adequacy of maintenance planning during operations [14, page 224].

COSTS:

The cost analysis involves direct and indirect costs of the operations as well as those of all the elements considered in the operations phase. As in earlier phases, the definition of cost categories should be consistent with the requirement of USAF and the ability to evaluate system performance against criteria resulting from system requirements.

FACILITIES:

The operations facilities include the physical plant, real estate, temporary structures, housing, intermediate shops, depots, etc., required to support operational and maintenance functions associated with the prime system, test and support equipment, and training equipment throughout the operations phase, storage for space/repair parts and data, quarters for operator and maintenance personnel, and training operations. Capital equipment and utilities are considered as part of facilities [6, page 9].

TEST AND SUPPORT EQUIPMENT:

Test and support equipment used in operations includes all tools, monitoring and checkout equipment, metrology and calibration equipment, work stands and handling equipment required to support scheduled and unscheduled maintenance actions associated with the system. This includes external test equipment and built-in test (BIT) equipment which is considered to be part of the system [6, page 8].

RELIABILITY/MAINTAINABILITY/AVAILABILITY:

Reliability, maintainability, and availability are those concepts (as defined earlier) which during operations, concern the prime system as well as the support and test equipment. Operations is usually the crucial phase in the assessment of adequacy of these characteristics, and is the source of the requirements that define maintainability, reliability and availability [14, page 180].

ORGANIZATION PLAN:

The organization plan for operations develops an organizational structure for the accomplishment of the tasks required in the operations phase, and includes the definition of activities and phasing required to implement the organization.

PERSONNEL AND TRAINING:

Personnel and training include the identification and programming of skills, number of people, and training needed to accomplish the activities of the operations phase.

TECHNICAL DATA:

Technical data identify and record for on-call use all technical information necessary for the efficient operation and support of the system [14, page 227].

SAFETY:

Safety analysis for operations identifies possible hazard areas and warning notices in the operating and maintenance procedured. Note that human factors are closely aligned with system safety, and that safety provides a critical input into all phases of the life cycle while it is either a constraint or a criterion in the development of the system.

MANAGEMENT INFORMATION:

The management of operations information consists of assembling data into a manageable aggregate for user evaluation. It provides the feedback to the designer as well as to the user from the system concerning conditions about the state of operations activities. It also usually requries some formatting and analysis, and is the major input to management for on-going decisions during the operations phase [14, page 232].

ENVIRONMENTAL:

Environmental considerations in the operations phase include all effects of the environment on the system, the user, and all constituent elements.

RETIREMENT PHASE

ELEMENTS:

- FUTURE DEMAND
- SUPPLY SUPPORT
- MAINTENANCE PLANNING
- COSTS
- FACILITIES
- TEST AND SUPPORT EQUIPMENT
- ORGANIZATION PLAN
- PERSONNEL AND TRAINING
- TRANSPORTATION AND HANDLING
- SAFETY
- MANAGEMENT INFORMATION
- ENVIRONMENTAL

FUTURE DEMAND:

In the retirement phase, future utilization of the system and/or its components must be considered as it relates to technical obsolescence, wear and tear, adaptation to evolving needs, material disposal, etc.

SUPPLY SUPPORT:

The supply support during retirement consists of all repairable spares (units, assemblies, modules, etc.), repair parts, consumables, special supplies and related inventories needed to support scheduled and unscheduled maintenance actions associated with the prime equipment, facilities, and test and support equipment during the retirement phase. Considerations include each maintenance level and each geographical location where spare/repair parts are distributed and stocked, the distances between stockage points, and the methods of material distribution [6, page 8].

MAINTENANCE PLANNING:

Maintenance planning for retirement defines the support requirements and plans for maintenance in order to satisfy operational goals during the retirement phase. Concepts and requirements for each level of equipment maintenance to be performed are established [14, page 224].

COSTS:

The cost analysis involves the direct and indirect costs of the retirement of the system as well as the costs of all the elements considered in the retirement phase. As in earlier phases the definition of cost categories should

be consistent with the requirements of USAF and the ability to evaluate system performance against criteria resulting from system requirements.

FACILITIES:

Facilities needed during the retirement phase include the physical plant, real estate, temporary structures, housing, intermediate shops, depots, etc., required to support the deactivation, disassembly, storage, redistribution, destruction, etc., of the system, test and support equipment, training equipment, and training operations. Capital equipment and utilities are considered as part of facilities [6, page 9].

TEST AND SUPPORT EQUIPMENT:

Test and support equipment used in the retirement phase includes all tools, monitoring and checkout equipment, metrology and calibration equipment, work stands and handling equipment required to support scheduled and unscheduled maintenance actions associated with the retired system [6, page 8].

ORGANIZATION PLAN:

The organization plan for retirement of the system develops an organizational structure for the accomplishment of the tasks required in the retirement phase.

PERSONNEL AND TRAINING:

Personnel and training considerations during retirement include the identification and programming of skills, number of people, and training needed to accomplish the activities of the retirement phase [14, page 228].

TRANSPORTATION AND HANDLING:

The transportation and handling needs of the retirement phase include special provisions, reusable containers, and supplies necessary to support packaging, preservation, storage, handling, and/or transportation of the primary system, support equipment, spare/repair parts, personnel, technical data, and facilities [6, page 9].

SAFETY:

Safety considerations during the retirement phase are needed to protect the user against failures due to aging and obsolescence of the system, as well as the activity

to withdraw the equipment from active inventory.

MANAGEMENT INFORMATION:

The management of information during retirement consists of assembling data into a manageable aggregate for user evaluation. It provides the feedback to the designer as well as to the user from the system concerning conditions about the state of the retirement activities. It also usually requires some formatting and analysis [14, page 232].

ENVIRONMENTAL:

Environmental considerations during the retirement phase include the methods of disposal which must be consistent with ecological and environmental requirements. This involves the study of the effects of the retirement of the system on the environment [6, page 275].

APPENDIX B

HUMAN FACTORS REFERENCE BASE

This appendix is an adaptation of the bibliography on the morphology of design with inclusion of human factors [15]. The appendix provides a bibliography of human factors literature of interest to systems designers and represents an initial effort aimed at demonstrating the feasibility of bridging the communications gap between the systems design engineer and the human factors specialist. This effort is limited to the extent necessary to accomplish this goal. A reference list of some form is necessary if the design engineer is to include relevant criteria into the design analysis to insure adequate consideration of the inclusion of human factors in system design. Hopefully, this bibliography will provide an adequate basis for the inclusion of each respective human factor.

The human factors reference base relates the current literature to the previously defined thriteen human factors categories (see Para. 4.3) and provides a basis for establishing a formal three dimensional relationship among human factors, the steps in the design morphology, and the existing literature. Note that this relationship is best represented by a three dimensional matrix. The bibliography [15] is reviewed and the individual references which pertain to specific human factors are sorted with regard

to the human factor category or categories to which they refer. The thirteen groups of references are then numbered to facilitate access. For example a reference number of 7.0 refers to all the references listed in human factors category number seven (Man-Machine Interface), while a reference number of 7.2 refers specifically to article number two (2) in category number seven (7).

Future study should extend these reference lists and attempt to identify "standard" data elements of importance to system design for given classes of equipment.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This research report is intended to provide a basic clarification of the decision structure and methodology for the design of a high technology, large scale system with emphasis on integration of human factors and their associated metrics. The report summarizes and relates the design morphology to current USAF methodology for the management of system design, defines and classifies human factors which influence the decision structure of design, and clarifies the nature of subjective and objective requirements which are

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inputs to the decision structure. The conceptual framework developed as an effective approach to the solution of the problem of human factors inclusion into the design morphology is that of a three dimentional matrix representing the relationship among human factors, the design steps, and the current literature. This relationship allows for explicit human factors inclusion during the preliminary design phase of a new system and the resultant inclusion in the criteria function for the optimal design configuration.